Geochemistry and Petrology of Howardite Miller Range 11100: A Lithologically Diverse Piece of the Vestan Regolith

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Abstract

The howardite-eucrite-diogenite (HED) clan of meteorites, which most likely originate from the asteroid Vesta, provides an opportunity to combine in-depth sample analysis with the comprehensive remote sensing dataset from NASA's recent Dawn mission. Miller Range (MIL) 11100, an Antarctic howardite, contains diverse rock and mineral fragments from common HED lithologies (diogenites, cumulate eucrites, and basaltic eucrites). It also contains a rare pyroxferroite-bearing lithology – not recognized in HED until recently – and rare Mg-rich (Fo_{86-91}) olivine crystals that possibly represent material excavated from the Vestan mantle. Clast components underwent different histories of thermal and impact metamorphism before being

incorporated into this sample, reflecting the diversity in geological histories experienced by different parts of Vesta. The bulk chemical composition and petrography of MIL 11100 suggest that it is akin to the fragmental howardite meteorites. The strong lithological heterogeneity across this sample suggests that at least some parts of the Vestan regolith show heterogeneity on the mm-scale. We combine the outcomes of this study with data from NASA's Dawn mission and hypothesize on possible source regions for this meteorite on the surface of Vesta.

1. Introduction

It is a widely accepted hypothesis that the HED (howardite + eucrite + diogenite) clan of achondritic meteorites originates from the asteroid Vesta (Binzel and Xu, 1993; Drake, 2001), although Wasson (2013) discusses alternative parent body hypotheses. Vesta is the only known intact differentiated asteroid in the Asteroid Belt (Keil 2002) and, alongside Ceres, was a main target of NASA's ongoing Dawn mission (Russell et al. 2004). Dawn was in orbit around Vesta between July 2011 and September 2012 (Schäfer et al. 2014), and the data it collected further strengthened the case that HED meteorites originate from this asteroid (McCoy et al. 2015). Thus, the strong HED–Vesta link provides a unique opportunity to combine meteoritic sample analysis with asteroid remote-sensing data. A brief overview of our current understanding of HED meteorites and Vestan geology is outlined below.

Whilst their petrogenesis is not yet fully understood, eucrites are generally considered to represent ancient surface lava flows, shallow crustal intrusions, and mid–lower crustal cumulates (Mittlefehldt et al. 2013). Eucrites are mostly composed of pigeonite and plagioclase, and are broadly divided into two subtypes (see Mittlefehldt 2015 and refs. therein for a review of HED petrology): cumulate eucrites, which are medium- to coarse-grained gabbros, and basaltic eucrites, which are fine-grained basalts.

Diogenites are coarse-grained ultramafic cumulates (Mittlefehldt 1994). While most are orthopyroxenites, comprised mostly of orthopyroxene (85-100 vol%) and accessory amounts of

53 olivine, chromite, and plagioclase (Beck and McSween 2010), some diogenites are dunites,
54 harzburgites, or norites (Wittke et al. 2011). The two leading models describing their petrogenesis
55 are that diogenites are cumulates that formed at the bottom of a magma ocean (Ikeda and Takeda
56 1985; Righter and Drake 1997), or alternatively that they are shallower intrusions into a pre-existing
57 eucritic crust (Yamaguchi et al. 2011).

58 Howardites are polymict breccias (Bunch 1975) that represent the lithified regolith of Vesta. To
59 a first approximation, they are composed of eucrite and diogenite fragments in varying proportions
60 (Delaney et al. 1983). These fragments vary in nature and include polymineralic lithic fragments,
61 monomineralic fragments, impact glasses, melt breccias, and other breccia fragments. Recently,
62 howardites have been divided into two subtypes: regolithic howardites and fragmental howardites
63 (Warren et al. 2009; Cartwright et al. 2013, 2014). Regolithic howardites represent well-mixed and
64 ancient samples of the active near-surface regolith that experienced extensive gardening
65 (reworking) by micro-meteorite impacts and have a solar wind, fractionated solar wind, or a
66 planetary (from the presence of exogenic carbonaceous material) noble gas isotopic signature
67 (Cartwright et al. 2013). Some howardites contain exogenic clasts of carbonaceous chondrite
68 asteroid debris, mostly derived from the phyllosilicate-bearing CM2 group (Zolensky et al. 1996),
69 but also from the CR2 group (Gounelle et al. 2003). Fragmental howardites represent less well-
70 mixed howardites that did not originate from the active portion of the regolith (Cartwright et al.
71 2013). They are polymict breccias and have a cosmogenic-isotope dominated noble gas signature
72 that is produced by the interaction of high-energy cosmic rays with target atoms at depths on the
73 order of 1 m (Wieler 2002).

74 Warren et al. (2009) suggested five parameters that can be used to distinguish a regolithic
75 howardite from a fragmental howardite: the presence of impact spherules, bulk Ni concentration
76 exceeding 300 $\mu g\ g^{-1}$, bulk Al_2O_3 concentration of 8–9 wt%, a eucrite to diogenite component ratio
77 of 2:1, and a solar wind noble gas signature. However, Cartwright et al. (2013) found that a solar

78 wind or planetary-isotope noble gas signature is the only appropriate metric by which regolithic
79 howardites can be distinguished from fragmental howardites.
80 Miller Range (MIL) 11100 is a howardite, which upon collection from Antarctica in 2011 by
81 the Antarctic Search for Meteorites program (ANSMET) had a mass of 130.8 g. Howardites are
82 scientifically important because they can provide information about both the magmatic evolution
83 and the impact history of their parent body. Here we present a bulk-rock geochemical,
84 mineralogical, and petrographic characterization of MIL 11100, and link these observations with the
85 regolith nature of this sample and data from NASA's Dawn mission.
86
87 **2. Methods**
88 2.1 Sample preparation
89 Of the original 130.8 g stone found in Antarctica, we were allocated a thin section and a 283.5
90 mg chip. The thin section, MIL 11100,9, has a thickness of 30 μm and a surface area of 73 mm^2,
91 and was prepared by the meteorite curation lab at NASA's Johnson Space Centre. A 122.2 mg
92 portion of chip was removed for bulk chemical analysis and powdered in an agate pestle and mortar
93 in a class 100 clean room at the University of Manchester.
94 2.2 Petrography and compositional variability
95 Preliminary textural analysis and mineral identification of MIL 11100,9 were conducted using
96 optical transmission microscopy. The textural analysis of MIL 11100,9 was then conducted by
97 studying a back-scattered electron (BSE) mosaic of the entire sample (see Fig. 3), acquired using a
98 Phillips XL30 FEG environmental scanning electron microscope (ESEM) and EDAX Si(Li) EDS
99 detector at the University of Manchester, with a magnification of ×400 and beam energy of 15 keV.
100 High resolution BSE images of interesting clasts and mineral fragments (up to ×1200) were
101 collected using the same setup. X-ray element maps of MIL 11100,9 were also collected for C, O,
102 Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Co, and Ni using the following settings:

magnification of ×250, 8 frames per tile, 512 × 400 pixels per tile, 200 µs dwell time per pixel, at ~6.5 minutes per frame (Figs. S2-S13, supplementary material).

2.3 Mineral chemistry

Quantitative mineral compositional analysis of MIL 11100,9 was conducted using a CAMECA SX100 Electron Probe Microanalyser at the University of Manchester calibrated using natural minerals and metals; Co-metal (CoO), Ni-oxide (NiO), tephrite (MnO), fayalite (FeO), halite (Cl), troilite (S), wollastonite (CaO and SiO_2), ilmenite (TiO_2), K-feldspar (K_2O), apatite (P_2O_5), Cr_2O_3 (Cr_2O_3), corundum (Al_2O_3), jadite (Na_2O), and periclase (MgO). Background settings were chosen to avoid peak overlap issues. Stoichiometric processing was conducted on all analyses, and only values above the instrumental detection limits and with oxide analytical totals of 100 ± 2% were used. To analyze silicate minerals, a beam energy of 15 keV was used with a beam current of 20 nA and a spot-size of 1 µm. Precautions were taken when analyzing glasses to minimize sample damage by using a defocused beam with a spot-size of 20 µm.

2.4 Bulk rock composition

The bulk rock composition of MIL 11100,7 was determined by inductively coupled plasma mass spectrometry (ICP-MS) using an Agilent 7700x instrument and inductively coupled plasma optical emission spectroscopy (ICP-OES) using a Thermo iCap 6500 Duo spectrometer at the Natural History Museum, London. Concentrations of 10 major and minor elements including Cr were determined by ICP-OES. For this, 40 mg of sample was fused with 120 mg of $LiBO_2$ in a Pt/Au crucible and the resulting flux dissolved in 10% HNO_3. Calibration was performed using certified reference materials (CRM) prepared in the same way. Concentrations of 38 trace elements as well as K_2O were determined by ICP-MS from a separate portion of ~50 mg of powdered sample after HF + $HClO_4$ + HNO_3 digestion. To minimize polyatomic interferences, the instrument was operated with 5 mL/min He (99.9995% purity) in the collision–reaction octopole cell (CRC) as well as with no collision gas entering the CRC. Non-isobaric interferences in the ICP-MS analysis were minimized by tuning CeO^+/Ce^+ to <0.2% (in He mode) and Ba^{++}/Ba^+ to <1% (both modes). Even

129 though in the He mode most polyatomic interferences are negligible, additional mathematical
130 corrections were performed to correct for polyatomic interferences on Eu, Gd, Tb, Hf , Ta and W
131 caused by Ba, Ce+Pr, Nd, Dy, Ho, and Er respectively (Ferrat et al. 2012; Strekopytov and Dubinin
132 1997). Sulfur was determined by ICP-OES after acid digestion. Between 3 to 10 repeat
133 measurements of the sample were conducted on different days and the precision of these replicates
134 are reported to 2 standard deviations in Table 1. The relative standard deviation ranges between
135 0.1% to 5.2% for the major elements, and 0.2 to 7.5% for the minor and trace elements. Accuracy of
136 the ICP-OES analysis was checked by analyzing NIM-D Dunite and STM-1 Shale CRMs and of the
137 ICP-MS analysis by analyzing BCR-2 Basalt, JLk-1 Lake Sediment, JLs-1 Limestone and DNC-1
138 Dolerite CRMs and was found satisfactory for all elements (Table S1, supplementary material).
139
140 **3. Results**
141 3.1 HED parentage
142 In the absence of oxygen isotopic data, bulk rock and mineralogical Fe/Mn ratios can be used
143 to determine meteoritic parentage (Karner et al. 2006; Papike et al. 2009). The average molar
144 FeO/MnO of pyroxene (31.3 ± 14.6 2stdev) and olivine (41.5 ± 4.3 2stdev) are consistent with that
145 of HEDs (Beck and McSween 2010; Hahn et al. 2015), and all but three pyroxene analyses lie along
146 the planetary Mn vs. Fe trends (Figs. 1a and 1b). The bulk rock FeO/MnO (36.8 ± 2.0 2stdev) of
147 MIL 11100,7 is also similar to that of other HEDs (Nittler et al. 2004) (Fig. 1c).
148 3.2 Rare earth element (REE) composition
149 The MIL 11100,7 bulk rock composition is summarized in Table 1. The bulk (REE)
150 concentrations and chondrite (CI) normalized (Anders and Grevesse 1989) REE pattern (Fig. 2) of
151 MIL 11100,7 are typical to those of howardites (see Table S3). The average REE concentrations of
152 HED groups were calculated by us by critical assessment of the dataset in Beck et al (2015) (see
153 Table S3, supplementary material). To obtain average REE concentrations for meteorite groups, all
154 analyses, for which at least some REE including Eu were reported in Beck et al. (2015), were used.

Of these analytical sets, only those that show no significant anomalies for elements other than Ce and Eu in the CI-normalized patterns were selected as being the most analytically sound, and the average was calculated. The average REE concentrations for diogenites are calculated based on the data for up to 51 meteorites; the average for basaltic eucrites, up to 67 meteorites; the average for cumulate eucrites, on the data for 7 meteorites (only 4 of them had Gd concentrations, and average Pr and Tm concentrations could not be estimated); the average howardite pattern was calculated based on the analyses of up to 60 meteorites (Table 2). The CI-normalized pattern for MIL 11100,7 lies between the average CI-normalized pattern of basaltic eucrites and howardites (Fig. 2). Given that howardites are a mixture of clasts of diogenites, cumulate eucrites, and basaltic eucrites, it is unsurprising that the REE pattern of MIL 11100,7 (as well as the average howardite) lies between the average basaltic eucrite (REE-enriched) and the REE-depleted cumulate eucrites and diogenites.

3.3 POEM and mixing trends

The POEM (percentage of eucritic material) of MIL 11100,7 can be calculated using the method outlined by Mittlefehldt et al (2013), where the POEMs with respect to Ca and with respect to Al are calculated and averaged as shown in equation (1).

$$\mathrm{POEM_{sample}} = \left[\frac{\left(\frac{\mathrm{Ca_{mean\ bulk\ dio}} + \mathrm{Ca_{bulk\ sample}}}{\mathrm{Ca_{mean\ bulk\ dio}} + \mathrm{Ca_{mean\ bulk\ euc}}}\right) + \left(\frac{\mathrm{Al_{mean\ bulk\ dio}} + \mathrm{Al_{bulk\ sample}}}{\mathrm{Al_{mean\ bulk\ dio}} + \mathrm{Al_{mean\ bulk\ euc}}}\right)}{2}\right] \times 100$$

(Equation (1))

The POEM of MIL 11100,7 based on this method is ca. 70%, which represents a eucrite to diogenite ratio of 2.1:1. This is close to the eucrite to diogenite ratio of 2:1 typical of regolithic howardites (Warren et al. 2009).

3.4 Petrography

MIL 11100,9 is composed of fragmented clasts surrounded by a fine-grained clastic matrix (Fig. 3). Pyroxene is the most common mineral (~85% by sample area), followed by plagioclase (~15% by sample area). Minor minerals make up <2% by area of the sample and include olivine, metal grains, Ti-rich ilmenite, spinel, chromite, and Si-rich phases. There are distinct compositional regions in the sample characterized by Mg-poor silicates, mixed with more heterogeneous regions that contain both Mg-rich and Mg-poor silicates (Fig. 3d). These regions are visible on the mm-scale and the boundaries between them are very sharp. The grains are finer in the Mg-poor regions than the Mg-rich regions. The Mg-poor regions represent purely eucritic material and, in this thin section, seem to be contained within a better-mixed (polymict) howarditic material. Based on the percentage surface area of the two compositional regions, MIL 11100,9 is composed of 46% purely eucritic material and 54% howarditic (both eucritic and diogenitic) material.

Clasts vary in composition and include simple monomineralic fragments (Figs. 4b and 4c), polymineralic lithic fragments (Fig. 4a), cataclastic breccias (Figs. 4h and 4i), clast-rich and clast-poor impact melt breccias (Figs. 4j and 4k), crystalline impact melt breccia (Fig. 4l), granulitic clasts (Fig. 4g), and metal, sometimes affiliated with silicate symplectite assemblages (Figs. 4d-4f). Clasts are angular to sub-rounded and range from coarse (2.3 mm maximum) to very fine-grained (indistinguishable from the sub-µm matrix) (Fig. 3), a texture typical of howardite breccias (Bunch 1975). Clasts and mineral fragments exhibit a range of shock metamorphic grades, from unaltered mineral phases to complete maskelynization of plagioclase and fracturing of pyroxene, offsetting exsolution lamellae.

3.5 Mineral chemistry

Mineral chemistry is summarized in Tables S4-S7 (supplementary material) and the locations of clasts described in these tables are shown in Fig. S1 (supplementary material). The composition of clasts highlighted in Fig. S1 are summarized in Figs. S18 and S19 (supplementary material).

3.5.1 Pyroxene

Pyroxene is present in a wide range of clast types, including monomineralic fragments, polymineralic lithic fragments, impact melts, and lithic breccia clasts. Pyroxene range in composition from high- to low-Ca (Fs_{16-86}, En_{8-83}, Wo_{1-41}) and are mostly similar in composition to basaltic eucrites and diogenites, with few similar in composition to cumulate eucrites (Fig. 5). The diogenitic and cumulate eucritic pyroxene in this sample are exclusively low-Ca, whereas the basaltic eucritic pyroxene ranges from high- to low-Ca (Fig. 5). The Mg# (molar Mg/[Mg+Fe] × 100) of the pyroxene in MIL 11100,9 ranges from $Mg\#_{8-85}$ (Fig. 5), spanning in composition from the relatively evolved basaltic eucrites to the more primitive diogenites. Most Mg# values are similar to basaltic eucrites and diogenites (Mittlefehldt 2015).

3.5.2 Plagioclase

Plagioclase is present in a range of clast types, including polymineralic lithic fragments (Fig. 4a), clast-rich (Fig. 4k) and clast-poor (Fig. 4l) impact melt breccias, cataclastic breccia clasts (Fig. 4h-4i), and as maskelynite in crystalline impact melts (Fig. 4l). Plagioclase is similar in composition to other HEDs and is relatively uniform in composition throughout MIL 11100,9, having low-K and high-Ca ($Or_{0-1.8}Ab_{5-23}An_{75-95}$: Fig. 6). These compositions are more similar to basaltic eucrites and diogenites, while cumulate eucrites do not have a large overlap with the plagioclase in MIL 11100,9 (Mittlefehldt 2015).

3.5.3 Olivine

Monomineralic olivine mineral fragments (of up to 200 μm) in MIL 11100,9 are forsteritic in composition (Fo_{86-91}: Fig. 7) – above the diogenitic olivine compositional range of Fo_{78-61} (Beck et al. 2012). Although uncommon, similar forsterite-rich olivine has been identified in howardites in previous works (e.g., Beck et al. 2012; Lunning et al. 2014; Hahn et al. 2015). The locations of these Mg-rich olivine fragments are highlighted in Fig. S3 (supplementary material).

Olivine grains identified in polymineralic lithic breccias (Fig. 4h and Fig. 4i) and clast-bearing impact melt breccias (Fig. 4j and Fig. 4k) have compositions of Fo_{14} and Fo_{43}, respectively (Fig. 7). In both cases, they are fractured and found in association with pyroxene, ilmenite, and plagioclase.

230 *3.5.4 Metal and oxides*

231 Mg-aluminous chromite is present as small anhedral grains (<50 μm) in a crystalline impact
232 melt breccia (Fig. 4l), making up <1% by clast area. Mg-aluminous chromite is also present in clast-
233 bearing impact melts, also making up <1% by area. The reader is referred to Table S7
234 (supplementary material) for a summary of oxide compositions.

235 3.6 Clast diversity

236 The following section will describe some of the clasts in this sample in more detail. A summary
237 of clast compositions and their location in the sample is found in Tables S4–S7 and Fig. S1
238 (supplementary material).

239 *3.6.1 Lithic igneous fragments*

240 Polymineralic lithic fragments that retain their original igneous texture are uncommon in MIL
241 11100,9. The largest lithic fragment (Fig. 4a; referred to as clast 5 in the supplementary material) is
242 texturally and mineralogically similar to a eucritic basalt (Mittlefehldt 2015). It is made up of
243 subophitic pyroxene and plagioclase in roughly equal proportions. A subhedral unequilibrated
244 texture is preserved in this fragment, with the plagioclase taking the form of euhedral laths
245 surrounded by interstitial anhedral pyroxene. The pyroxene has undeformed exsolution lamellae
246 with apparent thicknesses of 0.5 μm to <0.1 μm, and this clast is lightly fractured, indicating that it
247 has not undergone much cataclasis. Low- and high-Ca pyroxene grains similar to pyroxene in
248 basaltic eucrites are present in the lithic fragments ($En_{30-36}Fs_{44-62}Wo_{4-26}$). The continuum from low-
249 Ca (pigeonite) to high-Ca (augite) indicates chemical equilibration, and the high Fe# ($Fe\#_{65-58}$)
250 indicates that pyroxene crystallized from a relatively evolved magma. Molar Al/Ti ratios in the
251 pyroxene range from 3.1 to 0.4, indicating that it crystallized after the onset of the crystallization of
252 plagioclase (when plagioclase began co-crystallizing with pyroxene, Al continuously and
253 preferentially partitioned into plagioclase, so that less was available for the pyroxene, and caused
254 Al/Ti to decline with increasing Fe#: see discussion in Arai et al. 1996). The plagioclase is slightly

compositionally zoned ($Or_{0.4-1.0}Ab_{11-19}An_{80-88}$) and the most frequent compositions, An_{87} and An_{89} (Fig. 6), are similar to both basaltic eucrites and diogenites.

3.6.2 Pyroxene mineral fragments

Most of the clasts (~80 area%) in MIL 11100,9 are pyroxene mineral fragments, ranging in composition from diogenite-like to basaltic eucrite-like. While some fragments contain another mineral (<2% of surface area), most are monomineralic and similar to basaltic eucritic pyroxene in composition.

At 2.4 mm in diameter, the largest clast in the sample is a diogenitic pyroxene mineral fragment with a uniform composition of $En_{69-71}Fs_{26-29}Wo_{2-3}$, containing <1% of sulfide by area (Fig. 4b; referred to as clast 4 in the supplementary material). The sulfide runs through the sample as strings of sub-spherical blebs, ~10 μm in diameter. This fragment lacks internal texture or fabric and is heavily fractured.

Pyroxene mineral fragments, which are eucritic in composition, are typically exsolved to lamellae of pigeonite (Ca-poor) and augite (Ca-rich) with thickness from <1 μm to 10 μm. The equilibrium temperature of chemically equilibrated pyroxene (i.e., that with exsolution lamellae of high-Ca and low-Ca pyroxene) can be assessed using the method of Lindsley and Anderson (1983). Equilibrium temperature isotherms (Fig. 8) range from ~600 to ~900ºC. Some exsolution lamellae are deformed, offset, and sub-parallel, while other lamellae are undeformed and parallel (Fig. 4c), which reflects a range of levels of shock modification.

Some of these types of exsolved eucritic fragments are found with small mineral inclusions of plagioclase and/or a Si-rich phase (most likely quartz or tridymite). An example is shown in Fig. 4c (referred to as clast 9 in the supplementary material) containing a Si-rich mineral fragment. Here, the pyroxene is exsolved to pigeonite and augite ($En_{24-28}Fs_{35-70}Wo_{2-41}$), with lamellae widths ranging from <1 μm to 9 μm. While the lamellae are straight they are offset in places typically by <1 μm both in the presence and in the absence of fractures. This fragment is heavily cross-cut by

280 fractures, which together with the offset exsolution lamellae in the pyroxene, suggests at least a
281 small degree of cataclasis.

282 *3.6.3 Metal and associated pyroxferroite*

283 While most Fe-Ni metal (kamacite: Fe 99.6 wt%, Co 0.3 wt%, Ni <0.5 wt%) grains are
284 monomineralic, a large (400 μm) Fe-Ni grain (Fig. 4d; referred to as clast 1 in the supplementary
285 material) is present in association with pyroxferroite (a type of Fe-rich pyroxene) and a three-phase
286 symplectite assemblage (Figs. 4e and 4f; referred to as clast 1 in the supplementary material).

287 This grain is moderately fractured and oxidation in the fractures and around the rim is clearly
288 visible. The pyroxferroite (Fig. 4e) with a composition of $Fs_{81}En_{9}Wo_{12}$ is enriched in Fe in
289 comparison with other pyroxene grains in MIL 11100,9 (Fig. 5) and is the only grain that does not
290 follow the Fe–Mn planetary pyroxene trend (Fig. 1a). The pyroxferroite has broken down in places
291 to a three-phase (silica–fayalite–hedenbergite) symplectite (Figs. 4e and 4f), with a vermicular
292 ("worm-like") structure.

293 *3.6.4 Granulitic clast*

294 The granulitic clasts (Fig. 4g; referred to as clast 8 in the supplementary material) have
295 anhedral and sub-rounded minerals, with an average grain size of 25 μm, and with a soap-bubble-
296 like granoblastic polygonal texture. They are composed of pyroxene and a Si-rich phase (most
297 likely quartz or tridymite) in roughly equal proportions. The composition of the pyroxene,
298 $En_{28-29}Fs_{59-69}Wo_{3-13}$, is similar to that of pyroxene found in basaltic eucrites (Mittlefehldt 2015). The
299 pyroxene is finely exsolved to pigeonite and augite. The exsolution lamellae have apparent
300 thicknesses of 1 μm, and while they are undeformed and parallel within grains, they are randomly
301 orientated from grain to grain.

302 *3.6.5 Cataclastic lithic breccia clasts*

303 Some clasts are cataclastic lithic breccias, which reflect the re-working of at least some
304 material prior to its incorporation into MIL 11100. The best example of such a clast is a large (1.7
305 mm) polymineralic eucritic breccia (Figs. 4h and 4i; referred to as clast 13 in the supplementary

material), which contains pyroxene (~95% by area) and interstitial plagioclase (~5% by area) as well as olivine (<1% by area) and a Ti-rich phase (<1% by area). The range of compositions of pyroxene is $En_{25-31}Fs_{33-70}Wo_{1-41}$ and the range of compositions of plagioclase is $Or_{0.2-0.5}Al_{7-11}An_{89-93}$, similar to the composition of basaltic eucrites (Mittlefehldt 2015). The interstitial olivine is Fe-rich, with a composition of Fo_{14}. The exsolution lamellae in the pyroxene are randomly orientated from grain to grain (Fig. 4i) and exhibit fracturing and deformation. This suggests that this clast underwent cataclasis and some thermal annealing (modifying the grain boundaries) to a large extent prior to incorporation into MIL 11100,9, possibly due to impact processes on the parent body.

3.6.6 Clast-bearing impact melt breccias

Clast-bearing impact melt breccias are uncommon in MIL 11100,9, usually with clast components that are on the order of a few hundred μm in size and display a wide range of textures and mineralogy.

A polymict clast-bearing impact melt (Fig. 4j; referred to as clast 2 in the supplementary material) is composed mainly of pyroxenous glass (65% by area), with smaller amounts of plagioclase (15% by area), pyroxene (20% by area), and olivine (<1% by area). The pyroxene fragments have compositions reflecting each of the main three igneous HED lithologies: diogenitic ($En_{69}Fs_{28}Wo_3$, Mg# = 71), cumulate eucritic ($En_{37}Fs_{45}Wo_{18}$, Mg# = 52), and basaltic eucritic ($En_{37}Fs_{45}Wo_{14-24}$, Mg# = 45). The plagioclase has a composition of An_{88-92} ($Or_{0.2-0.4}Al_{7-12}An_{88-92}$), similar to diogenites and basaltic eucrites. The olivine is subhedral and has a composition of Fo_{43} (Fig. 7), which is less Mg-rich than diogenitic olivine (Fo_{78-61}: Beck et al. 2012). The pyroxene in this clast ranges from amorphous (indicated by its optical isotropy) and heavily fractured, to being relatively unshocked (indicated by the straight and sub-parallel exsolution lamellae).

A clast-bearing impact melt breccia (Fig. 4k; referred to as clast 16 in the supplementary material) is composed of moderately fractured pyroxenous glass (~75% by area) and plagioclase (~25% by area). The pyroxene is similar in composition to cumulate eucrites, with a composition of

$En_{54-56}Fs_{31-33}Wo_{12-13}$. The plagioclase, enclosed within the pyroxene, has a composition of $Or_{0.2-0.3}Ab_7An_{93}$.

3.6.7 Crystalline impact melt breccias

While crystalline impact melts are uncommon in MIL 11100,9, a coarse grained (1.2 mm) notable example is present (Fig. 4l; referred to as clast 20 in the supplementary material). It is noritic and contains four minerals: low-Ca pyroxene (~92% by area), plagioclase (~8% by area), and minor amounts of a Si-rich phase and spinel ($Ti_{0.78-0.73}$; $Cr_{0.85-0.82}$; $Fe_{0.98-0.96}$) (each <1% by area). The plagioclase ($Or_{0.6-0.7}Ab_{12-13}An_{86-87}$), interstitial to the pyroxene, forms fine subhedral-anhedral laths with an average grain size of 30 μm. The subhedral pyroxene ranges in grain size from 10 to 200 μm, while the anhedral and interstitial Si-rich phase and metal oxides have grain sizes of <10 μm. The pyroxene grains exhibit clear compositional zonation, e.g. Mg-richer cores ($Mg\#_{72-60}$) surrounded by Mg-poorer rims ($Mg\#_{59-50}$). The Mg-rich cores are similar in composition to diogenites, while the Mg-poor regions are similar in composition to cumulate eucrites. The Al/Ti ratio of the pyroxene indicates that it crystallized both prior to and after the onset of plagioclase crystallization.

4 Discussion

4.1 Planetary origin of MIL 11100

The bulk major and trace element composition of MIL 11100,7 is consistent with the range of compositions exhibited by the HED meteorite group. The Fe–Mn systematics in pyroxene and olivine, and the bulk rock is also consistent with Fe–Mn systematics in other HED meteorites (Fig. 1).

While this study shows that MIL 11100 comes from the HED parent body, as with all HEDs it is not possible to prove beyond all doubt that it comes from Vesta. A sample return mission from Vesta would be necessary to (±dis)prove that HEDs originate from this asteroid, for example, by measuring its oxygen isotope composition. However, Vesta is currently the most likely candidate

for the HED parent body (McCoy et al. 2015) and by extension is the most likely parent body of MIL 11100.

4.2 Fragmental howardite, or a true regolithic howardite?

MIL 11100,7 has a Ni concentration of 26.7 μg g^{-1} (±2.2 μg g^{-1} 2stdev), and an Al_2O_3 concentration of 10.15 wt% (±0.14 2stdev). Based on the criteria proposed by Warren et al. (2009), MIL 11100 should be classified as a fragmental howardite because its Ni content does not exceed 300 μg g^{-1} and its bulk Al_2O_3 content is outside of the range of 8–9 wt%. However, these criteria were challenged by Cartwright et al. (2013) who showed that Ni content in HEDs is mostly controlled by the distribution of coarse grained chondritic clasts and metal grains. Small amounts of material (less than 100 mg) used in most published analyses makes it difficult to discuss representative Ni contents in individual meteorites. This notably highlights the problem encountered across meteoritics as a whole as to how much sample is required to properly represent a bulk meteorite composition. Even for analyses of relatively large bulk samples (>200 mg) of monomict HEDs, heterogeneously distributed accessory minerals can cause large variations in siderophile elements (e.g. Barrat et al. 2008). Thus, the cm-scale clast heterogeneity in MIL 11100,9 (Fig. 3d) makes it unlikely that our <100 mg bulk analysis is entirely representative of the bulk meteorite.

While MIL 11100 does not contain "impact spherules" it does contain clasts clearly formed during impact processes on Vesta, and the cm-scale heterogeneity exhibited by MIL 11100 is consistent with the view that fragmental howardites are less well-mixed than regolithic howardites (Warren et al. 2009; Cartwright et al. 2013).

Noble gas isotopic analysis is needed to definitively classify this howardite as either fragmental or regolithic howardite (Cartwright et al. 2013). However, the lack of impactor fragments in the sample suggests that this meteorite is more likely a fragmental howardite.

4.3 Origin and evolution of clasts

The full range of recognized igneous HED lithologies (diogenites, cumulate eucrites, and basaltic eucrites) are represented in MIL 11100. The varying evolutionary histories of different

384 regions of Vesta are reflected by the different thermal- and impact-metamorphic grades of clasts in
385 MIL 11100.

386 MIL 11100 underwent terrestrial alteration to weathering grade of W4 (Wlotzka, 1993) while
387 sat in/on the Antarctic ice-sheet, indicated by the oxidization of most metal-bearing clasts.
388 Terrestrial alteration was, however, relatively minor (at least for the chip of meteorite used for the
389 bulk analysis) as it did not lead to the formation of Ce anomaly in the bulk rock composition typical
390 of Antarctic HEDs that have been significantly altered on Earth (Mittlefehldt and Lindstrom, 1991).

391 *4.3.1 Pyroxferroite-bearing clast*

392 While the pyroxferroite associated with the Fe-Ni metal (Figs. 4d-4f) does not lie on the mafic
393 mineral Fe–Mn HED planetary pyroxene trend (Fig. 1a), the low Ni percentage of the Fe-Ni metal
394 with which it is associated is characteristic of eucritic metal (Duke, 1965). It is, therefore, unlikely
395 that this grain is an exogenous meteorite fragment. The unusual HED Fe-Mn mineral trends can
396 possibly be explained by a redox transformation of pyroxferroite, metastable at low pressures
397 (Aramovich et al. 2002), in which it exchanges Fe with the adjacent Fe-Ni metal, and Fe and Mn
398 with the breakdown symplectite products (Figs. 4d-4f).

399 Pyroxferroite has been observed in some martian meteorites (Aramovich et al. 2002), lunar
400 mare basalts (Lindsley et al. 1972), and other HED meteorites (Barrat et al. 2012). The conditions,
401 under which pyroxferroite is stable, correspond to core pressures on Vesta (Barrat et al. 2012).
402 However, since the Vestan core is likely composed of metallic Fe (Ruzicka et al. 1997) it is unlikely
403 that this lithology originated from the asteroid's core, and instead crystallized metastably in a low-
404 pressure environment (Lindsley et al. 1972). It is possible that the pyroxferroite formed from the
405 rapid cooling of a melt and was destabilized during a later reheating or high-pressure event (such as
406 post-crystallization metamorphism or an impact event). It has been suggested that low-Mg clasts
407 containing pyroxferroite represent highly evolved and unmetamorphosed Vestan lithologies with a
408 currently uncertain petrogenesis (Barrat et al. 2012), not recognized in the HED collection until
409 recently.

410 *4.3.2 Magnesian ($Fo_{>86}$) olivine fragments*

411 Mg-rich (Fo_{86-91}) monomineralic olivine fragments identified in this sample (discussed in
412 section 3.5.3) have been identified in other howardites, including Pecora Escarpment (PCA) 02009,
413 014, 015, 018, and 019 (Beck et al. 2012), and Yamato-7308 (Ikeda and Takeda 1985). Olivine with
414 a similar composition have also recently been identified in association with Mg-rich pyroxene
415 ($En_{>85}$) in what have been described as harzburgitic clasts in howardite Dominion Range (DOM)
416 10105 (Hahn et al. 2015). It has been suggested that such Mg-rich olivine in howardites and
417 observations of olivine of the Vestan surface (Ammannito et al. 2013; Le Corre et al. 2015;
418 Palomba et al. 2015) may represent either endogenous material originating from the Vestan mantle
419 (Lunning et al. 2014) or exogenous material from surviving silicate fragments of asteroid collisions
420 with the Vestan surface (e.g., Turrini et al. 2014; Le Corre et al. 2015).

421 Were the MIL11100,9 magnesian olivines delivered as meteorite fragments? As discussed
422 above, no 'lithic' meteorite fragments (previously identified in other howardite samples Zolensky et
423 al. 1996; Gounelle et al. 2003) have been located in MIL11100,9, and the sample appears in terms
424 of its bulk composition to be more like a fragmental breccia type than a regolithic breccia type that
425 has accumulated impactor debris. The FeO/MnO ratios of the olivine fragments (Fig. 1b) are
426 consistent with HED olivine trends, suggesting that they are from the same parent body rather than
427 an exogenous impactor. Indeed, the compositional range of the magnesian olivine (Fo_{86-91}) is
428 intermediate to olivine in ordinary and carbonaceous chondrites (Brearley and Jones 1998), and
429 instead has superchondritic Mg# vs MnO/FeO ratios, suggesting formation from an igneous
430 accumulation process. Thus, we suggest that a projectile silicate debris origin for the magnesian
431 olivine is unlikely, and a Vestan source is more probable.

432 Are the MIL11100,9 magnesian olivines from the Vestan mantle? If the fragments are from the
433 Vestan mantle they require a transfer processed to bring them from depth to the near-surface
434 howardite source setting. Are they fragments of mantle xenoliths? The absence of any other
435 diogenitic or other traceable material associated with these grains in MIL 11100,9 and the absence

436 of such olivine compositions in eucrite or diogenites (Lunning et al. 2014) suggest that they are not
437 likely originated from mantle xenoliths that were emplaced into the crust via igneous processes.
438 Future discovery of a forstertic ($Fo_{>86}$) olivine-bearing igneous eucrite or diogenites would shed
439 more light on this possibility.

440 Could they have been excavated by impacts and mixed as impactor ejecta into the howardite
441 regolith? The impactor size required to excavate through the eucrite and diogenite crust into the
442 underlying mantle is uncertain as we currently do not fully understand the subsurface structure of
443 Vesta, the depth of the Vestan Moho (crust-mantle boundary), and whether the Moho is evenly
444 distributed around the asteroid. If the Moho is only ~60 km thick, as Vestan magma ocean
445 differentiation models suggest (Clenet et al. 2014), then the combined excavation depth (60-100
446 km) of the Rheasilvia basin and the underlying older Veneneia basin on Vesta's south pole would
447 have possibly excavated Vestan mantle (Jutzi et al. 2013), exposing olivine at the asteroid's surface.
448 However, if Vesta's Moho is deeper than >100 km, as suggested by the alternative crustal growth
449 thickening model (Clenet et al. 2014), then the Veneneia–Rheasilvia basins may not have excavated
450 deep enough to access mantle material. Indeed, Dawn mission observations are at odds with the
451 Veneneia–Rheasilvia basin mantle excavation model: Ruesch et al. (2014) found a paucity of
452 olivine on Rheasilvia's central peak, and Palomba et al. (2015) found olivine-rich terrains occurring
453 more frequently on Vesta's northern hemisphere, associated with small impact craters <42 km in
454 size (Ammannito et al. 2013). So the cause of possible mantle extraction of olivine is still uncertain,
455 and further investigations to test the mantle origin of such magnesian olivine grains in howardites
456 are required.

457 *4.3.3 Ferroan ($Fo_{<14}$) olivine*

458 The fayalitic olivine Fo_{14} found in a cataclastic eucrite breccia clast in MIL 11100,9 (Figs. 4h
459 and 4i) is compositionally similar to the olivine found in the evolved eucrite Yamato 793164
460 (Mittlefehldt and Lindstrom 1993). Barrat et al. (2011) also report similar Fe-rich composition
461 olivine (Fo_{14-36}) in eucrites. However, the olivine grains described by Barrat et al. (2011) appear to

462 be related to fluid mobility on the parent melt as they were found located in pyroxene crack
463 networks in association with and anorthite (An_{97-98}). We do not think that the MIL 11100,9 fayaltic
464 olivine grains formed in this way as they are not confined to cracks in the brecciated clast (Fig. 4h
465 and 4i). They appear to be directly related to the eucite clast primary phases assembly.

466 *4.3.4 Granulitic breccia*

467 The pyroxene in granulitic breccia clasts is similar in composition to basaltic eucrites,
468 suggesting that basaltic eucrites were their protoliths. This observation is consistent with the
469 metamorphic evolution of eucrites: after the formation of the Vestan crust, the eucrites and
470 diogenites have often been modified by thermal metamorphism, impact brecciation, and impact
471 metamorphism (Yamaguchi et al. 1996). The exact cause of the ubiquitous and present at varying
472 degrees post-crystallization thermal metamorphism of the eucrites is somewhat unclear. Yamaguchi
473 et al. (1996) proposed a model in which crustal material was buried to greater depths as the crust
474 grew in thickness due to globally accumulating surface lava flows. Yamaguchi et al. (2009) more
475 recently proposed that eucrites experienced a two-stage thermal metamorphic history, with short-
476 duration high temperature metamorphism caused by igneous intrusions and/or impacts after the
477 longer-duration global metamorphic burial. Other possibilities include regional thermal
478 metamorphism caused by emplacement of thick superheated ejecta blankets across the Vestan
479 surface by the Rheasilvia and Veneneia basin forming events.

480 *4.3.5 Crystalline impact melt breccias*

481 The diogenite-like pyroxene cores and eucrite-like pyroxene rims in the crystalline impact melt
482 breccia clast described in section 3.6.7 (Fig. 4l) indicate that this clast could have formed from an
483 impact that first excavated diogenitic protolith material from depth, and partially melted this rock in
484 an impact melt sheet dominated by melted eucritic target rocks. Then, upon cooling, residual
485 diogenite pyroxene grains were enclosed as xenocrysts (possibly acting as nucleation sites) in a
486 eucritic crystalline impact melt, resulting in the strong compositional zonation. If diogenites
487 originate from significant depth and not as shallow intrusions (e.g. Barrat et al. 2006, 2008), this

488 model would suggest that this clast formed in an impact that excavated to lower-crustal depths. The
489 Rheasilvia impact basin excavated to crustal depths sufficient to sample both eucritic and diogenitic
490 material (Ammannito et al. 2013; Mandler and Elkins-Tanton 2013), so perhaps this clast represents
491 a melt byproduct from this massive event.

492 4.4 The global Vestan Perspective

493 Hydrogen-rich regions on Vesta's surface, mapped by Dawn's Gamma Ray and Neutron
494 Detector (GRaND) (Fig. 9b), may correspond to OH-bearing phyllosilicate minerals likely
495 reflecting the spatial distribution and concentration of exogenous phyllosilicate-bearing
496 carbonaceous material (Prettyman et al. 2012, 2013; Turrini et al. 2014; McCoy et al. 2015). The
497 absence of evidence of carbonaceous material and low bulk-rock Ni content in MIL 11100 indicate
498 that it probably originated from a crustal region on Vesta that contains low surface concentrations
499 equivalent to <250 μg/g of bulk hydrogen content (i.e., exogenic component poor regolith areas)
500 (Figure 9b).

501 GRaND also mapped out the distribution of major rock-forming elements on the surface of
502 Vesta's regolith (Prettyman et al. 2013; McCoy et al. 2015), which are used to map the distribution
503 of surface lithologies (Fig. 9c) and the POEM (Fig. 9a). There are regions of howardite-, eucrite-,
504 and diogenite-rich lithologies on the surface of Vesta, and our POEM analysis (section 3.3) and
505 bulk sample composition (Table 2) indicate that MIL 11100 came from a howarditic or eucrite-rich
506 howarditic region (Fig. 9a and 9c).

507 Taken these observations together, and assuming (i) that MIL 11100 is derived from the near-
508 surface environment of Vesta, (ii) that the bulk composition of the heterogeneous MIL 11100,7
509 sample is generally representative of the types of regoliths mapped at the spatial scale of Dawn
510 GRaND instrument footprint (pixel) size (~300 × 300 km), and (iii) the regolith mapped by the
511 GRaND instrument is representative of the upper few meters of mixed regolith, we speculate about
512 possible source terrains for the meteorite ejection site. Similar attempts have previously been made
513 to connect lunar meteorite regolith breccia chemistry to lunar surface gamma-ray spectroscopy

514 datasets in order to investigate their possible launch sites (Gnos et al. 2004; Joy et al. 2011;
515 Calzada-Diaz et al. 2015).

516 Figure 9a, 9b, and 9c shows the most similar area on the POEM, hydrogen, and HED
517 distribution maps that match the properties of MIL 11100. Figure 9d combines this information and
518 shows the geographic region on Vesta that could represent the best match terrain for the origin of
519 MIL 11100 (see area outlined in Fig. 9d showing regoliths between ~30ºN and 70ºN and ~90ºE and
520 240ºE). We speculate that MIL 11100 was possibly launched from this region of Vesta. This area
521 corresponds to three different Vestan geological terrains as determined by projecting this area onto
522 a chronostratigraphic map (Fig. 9d) of Vesta: Pre-Veneneian aged (asteroidal flux model age is 4.6
523 to 2.1 Ga; lunar-derived model age is 4.6 to 3.7 Ga) cratered plains, Veneneian aged (asteroidal flux
524 model age is >2.1 to ~1 Ga; lunar-derived model age is 3.7 to 3.5 Ga) Saturnalia Fossae Formation,
525 and Rheasilvian-Marcian aged (asteroidal flux model age is ~1 to ~0.3 Ga; lunar-derived model age
526 is 3.5 to ~0.14 Ga) undifferentiated crater material (Williams et al. 2014). The three possible
527 terrains of origin together span a wide range of possible ages from 4.6 Ga to at least ~300 Ma or
528 ~140 Ma, depending on which chronology system is used: asteroidal flux model ages (O'Brien et
529 al. 2014) or lunar-derived model ages (Schmedemann et al. 2014).

530 Schäfer et al (2014) interpreted the Pre-Veneneian cratered highland material to be dominated
531 by eucrite-rich howardites, which could represent the oldest Vestan terrain. The characteristics of
532 MIL 11100 are similar to the characteristics of this terrain, so, based on this method, we suggest
533 that that MIL 11100 most likely originated from this chronostratigraphic unit.

534

535 **5 Conclusions**

536 MIL 11100 is lithologically diverse, containing a wide range of clast types that span in
537 composition to include all recognized HED lithologies (diogenites, cumulate eucrites, and basaltic
538 eucrites). This sample also contains two less well-documented lithologies: Fo-rich ($Fo_{>86}$) olivine,
539 and a Mg-poor ($Mg\#_8$) pyroxferroite-bearing clast. Fo-rich olivine ($Fo_{>78}$), found as monomineralic

grains within the matrix of this sample, possibly represents excavated material from the Vestan mantle (Hahn et al. 2015). Mg-poor pyroxferroite ($Mg\#_8$) may represent a HED lithology not recognized until recently that is hypothesized to have formed from the re-melting of eucritic crust (Barrat et al. 2012). This meteorite provides witness of how many crustal levels of Vesta can be represented in a single howardite .

The strong heterogeneity across this sample (distinct regions of howarditic material and eucritic material) suggests that at least parts of the Vestan show heterogeneity on the cm-scale. Clasts underwent different histories of thermal metamorphism and impact metamorphism before being incorporated into this sample, reflecting the diversity in geological histories experienced by different parts of the parent body (Vesta).

We use data from the recent DAWN mission to link the hand specimen sample to the big picture global view of Vesta. Using results of the GRaND instrument (Fig. 9) we speculate that MIL 11100 may have originated from a region of the upper crust in the northern latitudes of Vesta (between roughly ~30ºN-70ºN and ~90ºE-240ºE). The impact-derived clasts in MIL 11100 may represent impact-cratering products from the terrains in this region.

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757 **Figure captions**

758 Fig 1. Mn vs. Fe atoms per formula unit in (a) pyroxene and (b) olivine, and (c) bulk rock
759 FeO/MnO vs. bulk rock Mg# (Mg# = molar Mg/ [Mg+Fe] × 100). Data in (a) are compared with
760 pyroxene trends in HED meteorites, terrestrial basalts, lunar meteorites, and martian basalts.
761 Martian, HED, and terrestrial lines are from Papike et al. (2009), and lunar rocks from Joy et al.
762 (2014) and refs therein. HED line: Mn = [0.0268 × Fe] + 0.0059; MIL 11100,9 line: Mn = [0.0324 x
763 Fe] + 0.0002. Points that lie away from the HED trend are circled and are discussed further in
764 section 3.6.3. Data in (b) are compared with olivine trends in lunar meteorites (Joy et al. 2014),
765 terrestrial basalts, and Martian basalts (Papike et al. 2009), and other HED olivine analyses
766 (Mittlefehldt 2014). MIL 11100,9 line: Mn = [0.0244 × Fe]; MIL 11100,9 R^2 = 0.99. Data in (c) are
767 compared with other HED bulk rock analyses (from compilation of Nittler et al. 2004) where Fe is
768 assumed to be Fe(II).
769
770 Fig. 2. The (CI-normalised) REE composition of MIL 11100,7 compared to the average (CI-
771 normalised) REE composition of diogenites, cumulate eucrites, basaltic eucrites, and howardites.
772 Data for diogenites, eucrites, and howardites are critically selected from Beck et al. (2015), and all
773 data are summarized in Tables 2 and S3 (supplementary material).
774
775 Fig. 3. MIL 11100,9 thin section imaged in **(a)** cross-polarized transmitted light and **(b)**
776 backscattered electron (BSE) where fractures in the sample are black. **(c)** Montaged K_α X-ray
777 element maps of MIL 11100,9 constructed using method outlined by Niihara et al. (2013), where: Si
778 = blue; Mg = green; Fe = red; Al = white; Ca = yellow, and Ti = pink. Colored pixels represent the
779 spatial distribution of elements, and concentration can be qualitatively assessed by the brightness of
780 a pixel (brighter color = higher concentration, see Joy et al. 2011 for more details). Pyroxene
781 mineral grains are colored green or red, depending on their Fe (red) and Mg (green) content. The
782 orange phases are Ca-rich pyroxene. Mg-rich olivine is bright green. Plagioclase feldspar is grey-

white. Si-rich phases are blue. Ilmenite is pink. Fe-Ni metal grains are bright red. Cracks in the sample are black. **(d)** Mg K_α X-ray element distribution map of MIL 11100,9. Green pixels represent the spatial distribution of Mg, and concentration can be qualitatively assessed by the brightness of a pixel (brighter color = higher concentration). Areas dominated by Mg-poor silicates are outlined. Most of the green phases are pyroxene. Olivine which is highly enriched in Mg (Fo# > 80, where Fo# = molar Mg/[Mg+Fe] × 100) are the brightest green. Cracks in the sample are black. High-resolution versions of these whole sample images, along with additional image formats can be found in Figs. S1-S17 (supplementary material).

Fig. 4. BSE images summarizing the range of clast types in MIL 11100,9. (a) Polymineralic lithic fragment exhibiting a subophitic texture, which is similar to basaltic eucrites in terms of both mineralogy and mineral chemistry. It is lightly fractured, and the augite pigeonite exsolution lamellae in the pyroxene are straight, parallel, and undeformed. (b) Fragment of diogenitic pyroxene, with strings of anhedral Fe-sulfide blebs running throughout. It is the largest clast in MIL 11100,9 at 2.4 mm in diameter, and it is moderately fractured. (c) Fragment of pyroxene and a Si-rich phase, where the pyroxene is similar in composition to pyroxene in basaltic eucrites. It is moderately fractured, and the augite-pigeonite exsolution lamellae in the pyroxene are straight, parallel, and undeformed. (d) Fe-Ni metal clast with associated pyroxferroite and pyroxferroite-derived three-phase symplectite. This clast is moderately fractured, and Fe-oxide alteration product runs through the fracture and surrounds the grain. (e) Pyroxferroite in association with Fe-Ni metal, which has broken down in places to a three-phase symplectite assemblage. (f) Three-phase fine-grained symplectite assemblage (silica–fayalite–hedenbergite) in association with Fe-Ni metal, formed from the breakdown of metastable pyroxferroite. (g) Granulitic clast with a granoblastic "soap bubble" texture. (h) Cataclastic eucrite clast. (i) Close up of fragment shown in (h) where the augite-pigeonite exsolution lamellae in the pyroxene are sub-parallel and deformed within distinct pyroxene crystals, and between crystals the lamella vary in orientation. The olivine and plagioclase

809 are anhedral, and interstitial to the pyroxene. (j) Clast-bearing impact melt breccia dominated by
810 pyroxenous glass. (k) Clast-bearing impact melt breccia dominated by pyroxeneous glass and a
811 plagioclase mineral component. (l) Crystalline impact-melt breccia, dominated by zoned pyroxene
812 and euhedral laths of plagioclase. Mineral name abbreviation names are: pyx = pyroxene, pl =
813 plagioclase, ol = olivine, kam = kamacite, sym = symplectite assemblage (note: this is not a mineral
814 name), ilm = ilmenite, and sp = spinel.
815
816 Fig. 5. A summary of the composition of pyroxene in MIL 11100,9 compared to pyroxene in HED
817 meteorites (Mittlefehldt 2014). Mg# = molar Mg/[Mg+Fe] × 100.
818
819 Fig. 6. A summary of the composition of plagioclase in MIL 11100,9 compared with plagioclase in
820 HED meteorites (Mittlefehldt 2014) where An# is molar Ca/(Ca+K+Na).
821
822 Fig. 7. A summary of the composition of olivine in MIL 11100,9, where Fo# = molar Mg/[Mg=Fe]
823 × 100. Compositional range of diogenitic olivine from Beck and McSween (2010). Note that the
824 fifty-one analyses representing $Fo_{>78}$ olivine are taken from ten distinct olivine fragments.
825
826 Fig. 8. The range of pyroxene formation temperatures in MIL 11100,9, indicated by their
827 compositions. Data are re-projected using the method of Lindsley and Andersen (1983), and
828 isotherms on diagrams adapted from Lindsley (1983).
829
830 Fig. 9. Regions of the surface of Vesta mapped by Dawn that have similar geochemical properties
831 to MIL 11100 in terms of (a) POEM distribution (figure adapted from Prettyman et al. 2013) and
832 (b) hydrogen distribution (figure adapted from McCoy et al. 2015). (c) Shows the hypothesized
833 possible areas of origin when the boundaries from (a) and (b) are overlain on a HED distribution
834 map, and areas which are not howardite/howardite-rich eucrites (i.e. dissimilar to MIL 111000 are

835 excluded (figure adapted from Prettyman et al. 2013). (d) Shows the hypothesized possible area of
836 origin for MIL 11100 on Vesta when the boundary from (c) is overlain on a chronostratigraphic
837 map of Vesta (chronostratigraphic adapted from http://vestatrek.jpl.nasa.gov). Dashed and dotted
838 lines outline two major impact basins on Vesta: VB = Veneneia Basin, and RB = Rheasilvia Basin.
839

840 **Table captions**

841 Table 1. Bulk rock composition of MIL 11100,7 as determined by this study. Errors reported are 2
842 standard deviations on the basis of repeat analysis.

843

844 Table 2. Average concentrations ($\mu g\ g^{-1}$) of REE in diogenites, basaltic eucrites, cumulate eucrites,
845 and howardites based on the compilation of available published data. See Table S3 (supplementary
846 material) for the REE data for individual meteorites critically selected from (Beck et al. 2015).

847 Table 1. Bulk-rock composition of MIL 11100,7 as determined by this study. Errors reported are 2

848 standard deviations on the basis of repeat analysis.

849

Major element	**weight %**		**n**	**Technique**
	Average	**2 std**		
SiO_2	48.70	± 0.81	3	ICP/Li
TiO_2	0.538	± 0.020	3	ICP/Li
Al_2O_3	10.15	± 0.14	3	ICP/Li
Cr_2O_3	0.402	± 0.025	3	ICP/Li
FeO	18.25	± 0.05	3	ICP/Li
MnO	0.496	± 0.029	3	ICP/Li
MgO	11.54	± 0.17	3	ICP/Li
CaO	7.18	± 0.74	3	ICP/Li
K_2O	0.0286	± 0.0043	8	ICP-MS
Na_2O	0.442	± 0.020	3	ICP/Li
P_2O_5	0.0504	± 0.0016	3	ICP/Li
Total	97.79	-	-	-
Mg#	52.99	-	-	-
FeO/MnO	36.80	-	-	-
An#	89.55	-	-	-
Trace element	**µg g^{-1}**		**n**	**Technique**
	Average	**2 std**		
Li	6.43	± 0.41	6	ICP-MS
Be	0.192	± 0.013	6	ICP-MS
S	2086		1	ICP
Sc	26.8	± 0.96	3	ICP-MS
V	96.1	± 4.2	3	ICP-MS
Cr	3907	± 240	3	ICP/Li
Co	11.1	± 0.76	3	ICP-MS
Ni	26.7	± 2.2	3	ICP-MS
Cu	2.85	± 0.058	3	ICP-MS
Zn	3.33	± 0.13	3	ICP-MS
Ga	1.36	± 0.078	6	ICP-MS
Rb	0.236	± 0.030	9	ICP-MS
Sr	59.2	± 1.0	3	ICP-MS
Y	12.7	± 0.30	3	ICP-MS
Zr	31.8	± 2.3	3	ICP-MS
Nb	2.85	± 0.027	3	ICP-MS
Mo	0.175	± 0.015	3	ICP-MS
Sb	0.053	± 0.003	3	ICP-MS
Cs	0.00666	± 0.00028	3	ICP-MS
Ba	23.6	± 3.3	10	ICP-MS
La	2.07	± 0.015	3	ICP-MS
Ce	5.75	± 0.12	3	ICP-MS
Pr	0.810	± 0.003	3	ICP-MS
Nd	4.17	± 0.040	3	ICP-MS
Sm	1.347	± 0.007	3	ICP-MS
Eu	0.487	± 0.034	3	ICP-MS

Gd	1.97	± 0.10	3	ICP-MS
Tb	0.343	± 0.008	3	ICP-MS
Dy	2.35	± 0.057	3	ICP-MS
Ho	0.505	± 0.018	3	ICP-MS
Er	1.52	± 0.059	3	ICP-MS
Tm	0.222	± 0.015	3	ICP-MS
Yb	1.47	± 0.052	3	ICP-MS
Lu	0.225	± 0.008	3	ICP-MS
Hf	0.926	± 0.023	3	ICP-MS
Ta	0.155	± 0.003	3	ICP-MS
W	0.110	± 0.014	3	ICP-MS
Pb	0.293	± 0.023	3	ICP-MS
Th	0.310	± 0.021	3	ICP-MS
U	0.0765	± 0.0030	3	ICP-MS

Notes: std - standard deviation;

LOQ - limit of quantification;

n - number of analyses;

ICP/Li – ICP-OES analysis after $LiBO_2$ fusion;

ICP – ICP-OES analysis after acid digestion;

ICP-MS – ICP-MS analysis.

859 Table 2. Average concentrations (μg g^{-1}) of REE in diogenites, basaltic eucrites, cumulate eucrites,
860 and howardites based on the compilation of available published data. See Table S3 (supplementary
861 material) for the REE data for individual meteorites critically selected from (Beck et al. 2015).
862

	N	Diogenites	N	Basaltic eucrites	N	Cumulate eucrites	N	Howardites
La	51	0.120	67	2.84	7	0.396	59	1.66
Ce	44	0.331	66	7.50	6	1.20	58	4.40
Pr	37	0.0319	26	1.19			35	0.666
Nd	42	0.199	57	5.74	7	0.668	52	3.26
Sm	51	0.102	67	1.76	7	0.269	60	1.13
Eu	51	0.0204	67	0.634	7	0.342	60	0.360
Gd	42	0.133	27	2.50	4	0.293	38	1.39
Tb	45	0.0348	66	0.439	6	0.071	60	0.267
Dy	42	0.203	44	3.07	4	0.423	44	1.72
Ho	39	0.0574	45	0.633	5	0.108	52	0.38
Er	42	0.162	26	1.97	3	0.400	36	1.10
Tm	13	0.0285	11	0.311			31	0.174
Yb	50	0.202	67	1.80	7	0.360	60	1.08
Lu	50	0.0354	67	0.272	7	0.057	60	0.163

863

864 Notes: N is number of meteorites used in calculations.